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Further redshifts of 1-Jy radio sources*

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Summary. We have firm redshifts for a further 12 faint radio source identifications from the '1-Jy' complete radio-selected sample, two of which are galaxies with redshifts $z>1.5$. Another object has a provisional redshift that requires confirmation. Five of these identifications had previously been classified as QSOs on the basis of their optical morphology. Our spectroscopy shows that of these, one is definitely a galaxy and two have characteristics intermediate between those of 'normal' radio galaxies and those of 'normal' quasars, for instance broad Balmer emission but an extended optical image. Two of the eight identifications previously classified as galaxies have similar 'intermediate' properties. The remaining identifications have low-excitation narrow emission-line systems of the type seen in other 1-Jy radio sources by Allington-Smith *et al.* We confirm that the 1-Jy emission lines are a factor 2 weaker than those of 3C galaxies in the same redshift interval.

1 Introduction

This paper continues the work of Allington-Smith, Lilly & Longair (1985, Paper I) in measuring redshifts of faint radio source identifications in the '1-Jy' radio-selected sample (Allington-Smith 1982; Allington-Smith *et al.* 1982, hereafter APLGW). The sample is defined by 408-MHz radio flux density limits $1<S_{408}<2$ Jy and so is significantly fainter than the well-studied bright 3C sample defined by $S_{178}>10$ Jy (Laing, Riley & Longair 1983, see also Spinrad *et al.* 1985a).

*Based on data obtained at the Isaac Newton Group of Telescopes of the Roque de Los Muchachos Observatory, La Palma; Lick Observatory, University of California and the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.
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Consequently this sample allows us to explore a deeper region of the radio luminosity–redshift plane. This brings about two advantages. First, the sample contains a higher proportion of high-redshift sources than the 3C sample, which facilitates studies of specifically high-redshift objects (e.g. the stellar populations of radio galaxies – e.g. Lilly, Longair & Allington-Smith 1985). Secondly, by combining data from both the 1-Jy and 3C samples, we can overcome the ambiguity in the interpretation of data from single samples that arises because of the strong correlation between radio luminosity and redshift in flux-density limited samples. In this context, the 1-Jy sample is of particular importance since it is defined at the flux density where the differential radio source counts are most divergent from the predictions of uniform cosmological models in which no evolution is allowed. In other words, the 1-Jy sample contains the highest proportion of those sources responsible for the very strong evolution in number density that is inferred from the source counts (Longair 1966). Both these lines of research depend crucially on complete redshift information.

Sixty-nine per cent of the sample have optical identifications from CCD observations to a limiting magnitude of $r \simeq 23$ (APLGW) and a further 21 per cent have infrared detections only (Lilly *et al.* 1985). Originally, only 10 of the 59 members of the sample had measured redshifts. Paper I presented redshifts for 13 radio source identifications not previously observed and here we present redshifts for a further 13 of which one is provisional. The observations and data reduction are presented in Section 2 and in Section 3 we discuss the spectra of each source. The results are briefly discussed in Section 4. In a future paper we will discuss the implications of these new data for studies of both the evolution of stellar populations in radio galaxies and the cosmological evolution in number density of the extragalactic radio source population.

2 Observations and data reduction

The observations were made during 1985 and 1986 on four telescopes as described below.

(i) The Isaac Newton (2.5-m) Telescope (INT) at the Roque de los Muchachos Observatory, La Palma with the Durham–RGO Faint Object Spectrograph (FOS; Breare *et al.* 1987). This provides a wavelength range (in first order) of 4800–10500 Å at a scale of 10.7 Å pixel^{-1}. A slit width of 1.1 arcsec was used resulting in a resolution of 17 Å FWHM. The sky-subtracted spectra were reduced to a relative flux scale with atmospheric absorption features removed following the procedure of Breare *et al.* (1985).

Table 1. Summary of observations. 'ID' refers to the optical classification: G, galaxy; Q, QSO; I, having intermediate properties between G and Q, see Sections 3 and 4 for further details.

Name (B2)	*r* mag	redshift	ID	Observation
0824+35A	20.5	2.249	Q	INT
0835+37	19.5	0.396	G	Lick
0913+39	20	1.269?	Q	INT
0955+38A	19.5	1.394	I	Lick
1018+37	20.2	0.806	G	Lick
1025+39	18.4	0.361	G	KPNO
1049+38	20.9	1.018	I	INT
1104+36	18.0	0.393	I	Lick
1108+39	20.8	0.59	G	INT
1129+35	21.5	0.971	I	INT
1141+35	23	1.781	G	MMT
1230+34	23	1.533	G	KPNO
1245+34	19.5	0.409	G	KPNO

(ii) Mayall 4-m telescope of the Kitt Peak National Observatory (KPNO) with the Cryogenic Camera (de Veny 1982). The slit aperture was 3.2×400 arcsec^2 and the dispersion 4.3 Å pixel^{-1}. Focus variations over the chip yield a somewhat variable resolution of ≃12 Å.

(iii) Lick Observatory Shane 3-m telescope with a 420 lines mm^{-1} grism. The detector was an 800×800 TI CCD described by Lauer *et al.* 1984. The slit aperture was 2.1×120 arcsec^2 yielding a resolution of 12 Å.

(iv) Multi-Mirror Telescope (MMT) with the blue-reticon system (Schectman & Hiltner 1976; Latham 1982) using two discrete 2×3 arcsec^2 apertures and yielding a resolution of 10 Å. The detector has excellent sensitivity over the wavelength range 3300–4500 Å and useful response to 6000 Å.

For the last three sets of observations, the spectra were reduced to an absolute flux density scale using observations of spectrophotometric standards.

The observations and principal results are summarized in Table 1.

3 Results

Fig. 1 shows the resultant spectra for the 13 objects for which we have attempted to measure a redshift. Imperfectly subtracted night-sky lines are indicated by 'S', cosmic-ray events by 'C', atmospheric absorption features by 'A' and defective pixels by 'P'.

Table 2 lists the identified spectral features with their observed wavelengths, rest-frame equivalent widths (if measurable) and, for the spectrophotometric observations, line flux. A question mark (?) indicates uncertainty and a colon (:) a measurement with large uncertainty. The adopted redshifts of the objects are given in Table 1 and are based on the brightest emission lines in the spectra.

Individual sources are discussed below. Details of the radio and optical structure of these sources can be found in Allington-Smith (1982) and APLGW.

0824+35A. This object was originally classified as a QSO on the basis of its optical morphology. This classification is confirmed by the broad carbon lines and power-law continuum ($\alpha \simeq 2$).

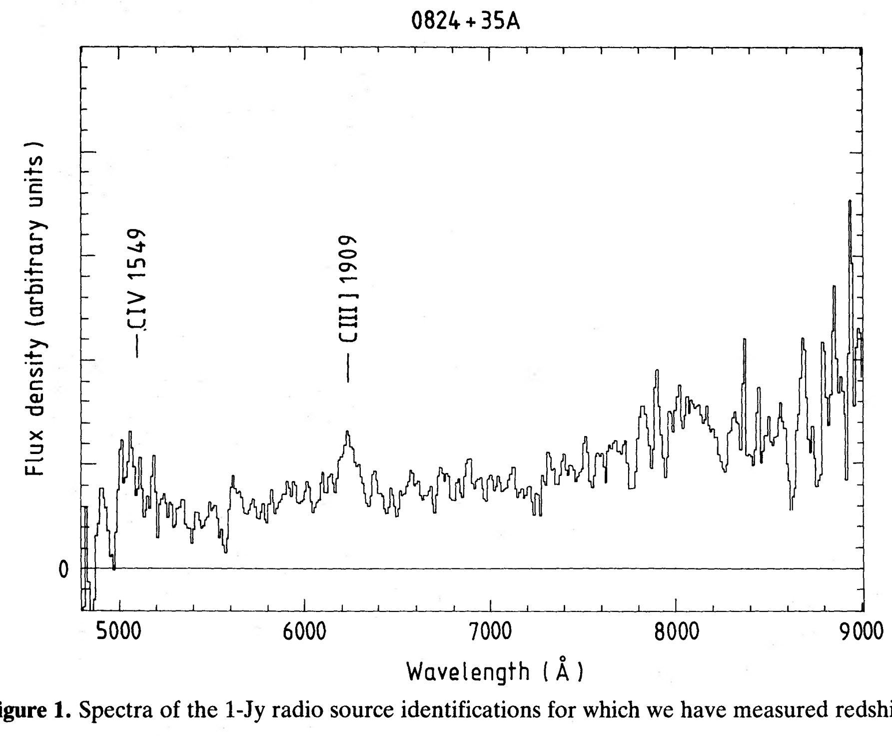


Figure 1. Spectra of the 1-Jy radio source identifications for which we have measured redshifts.

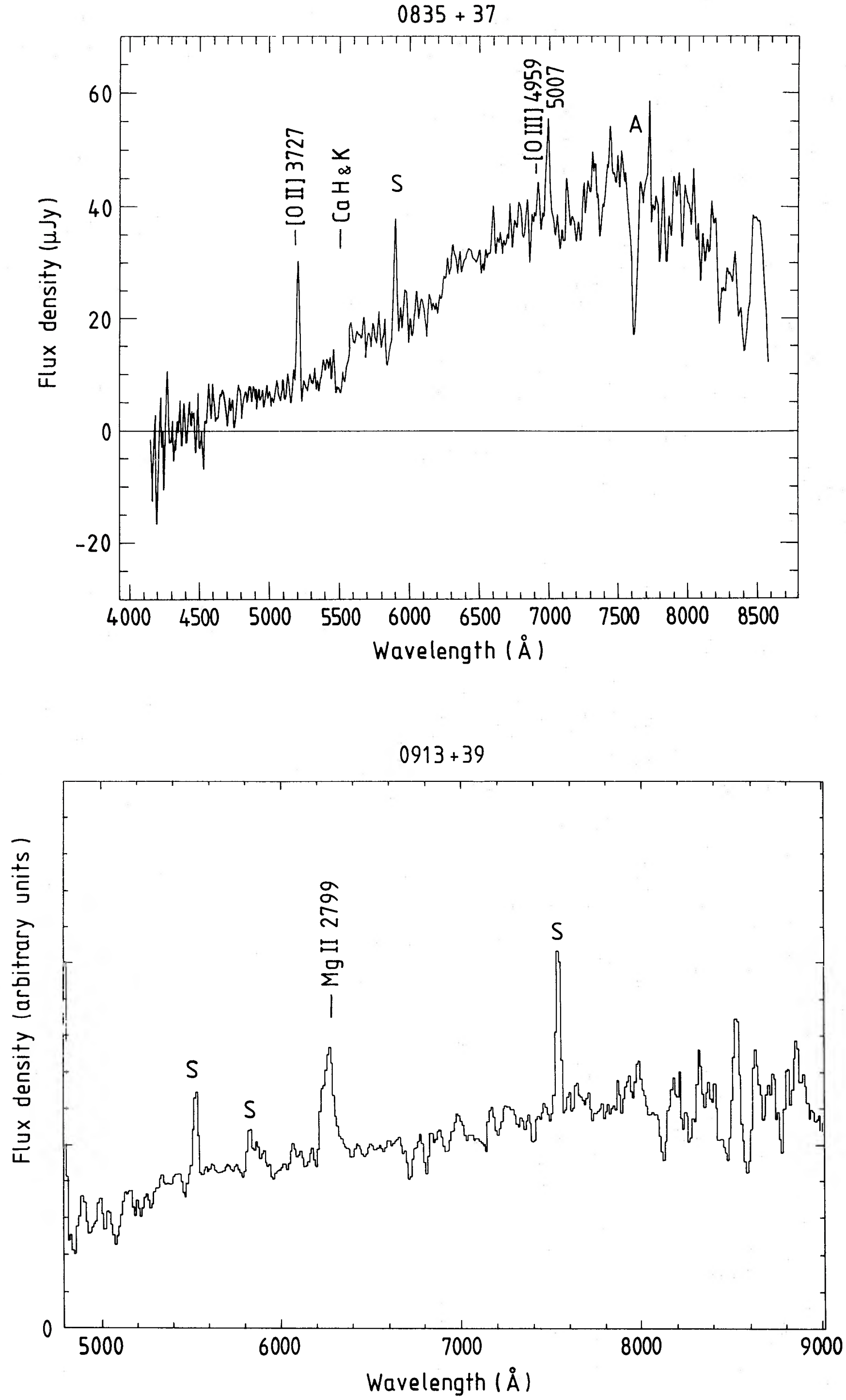


Figure 1 – *continued*

No Mg II $\lambda2799$ is detected, presumably because of the increasing night sky contamination longwards of 7000 Å. The redshift is 2.249.

0835+37. This object has a low-excitation narrow emission-line system and stellar absorption features, and is typical of the radio galaxies in Paper I. The redshift is 0.396.

0913+39. Originally classified as a QSO by APLGW, this object shows a strong power-law continuum ($\alpha \simeq 1$) with a single unambiguously detected broad emission line. This confirms the

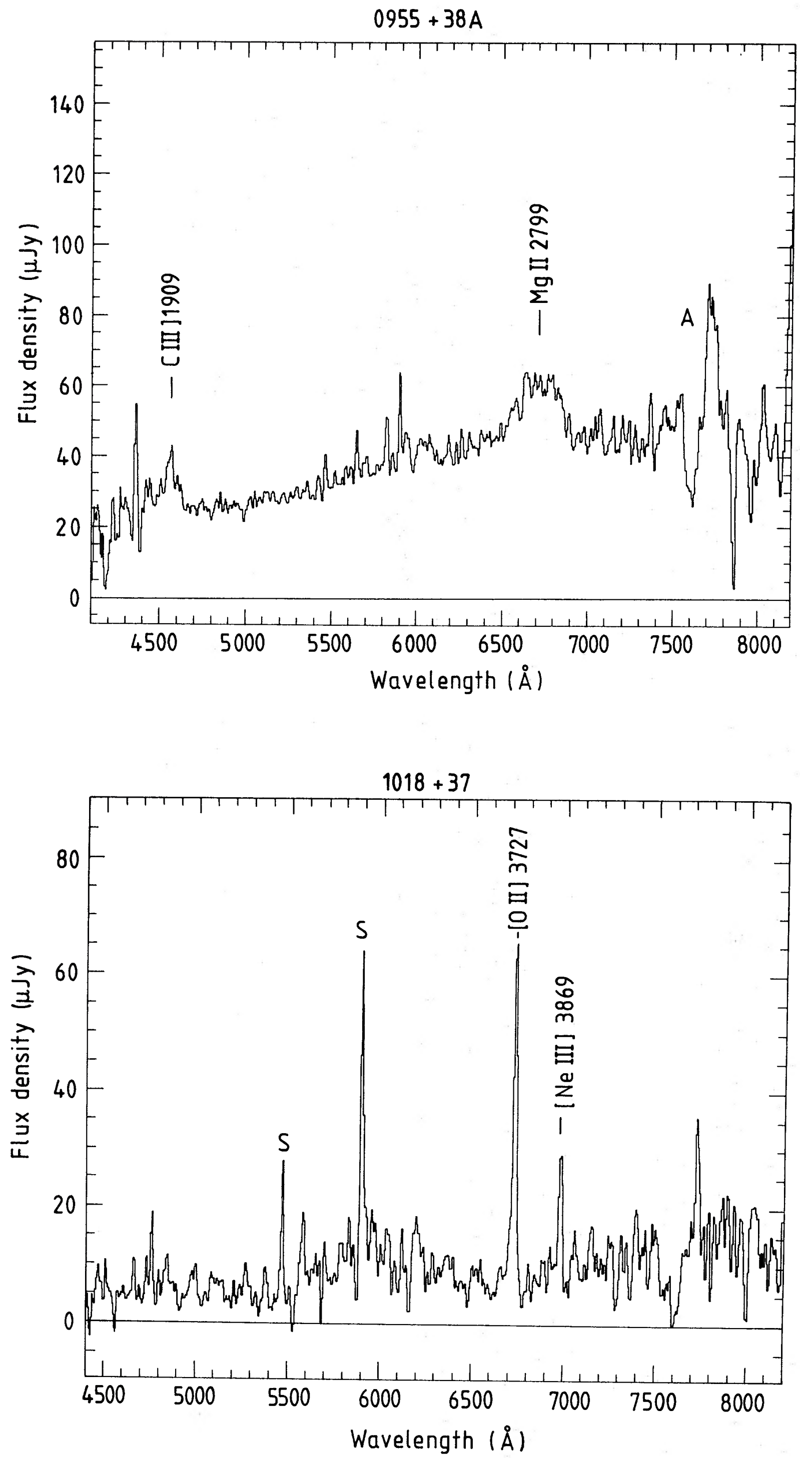


Figure 1 – *continued*

morphological classification but does not yield a firm redshift. By a process of elimination, we identify this line with Mg II λ2799, since any other identification should result in the presence of other identifiable lines in our spectrum unless it is grossly different from that of a typical QSO. If so, the redshift is 1.269, but this result must be considered as provisional since it is based on only a single line identification.

0955+38A. This object was originally classified by APLGW as a galaxy but the spectrum has

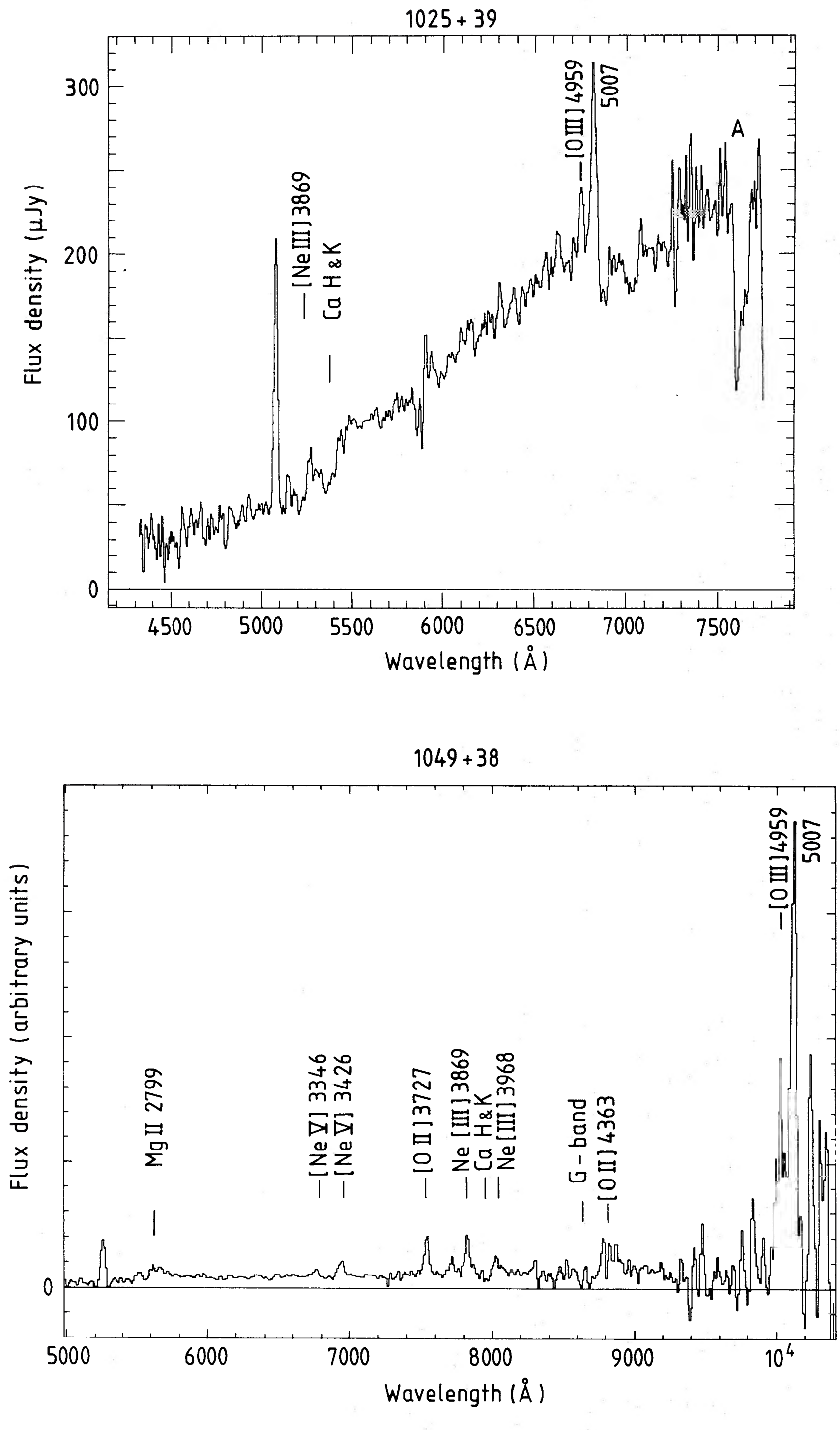
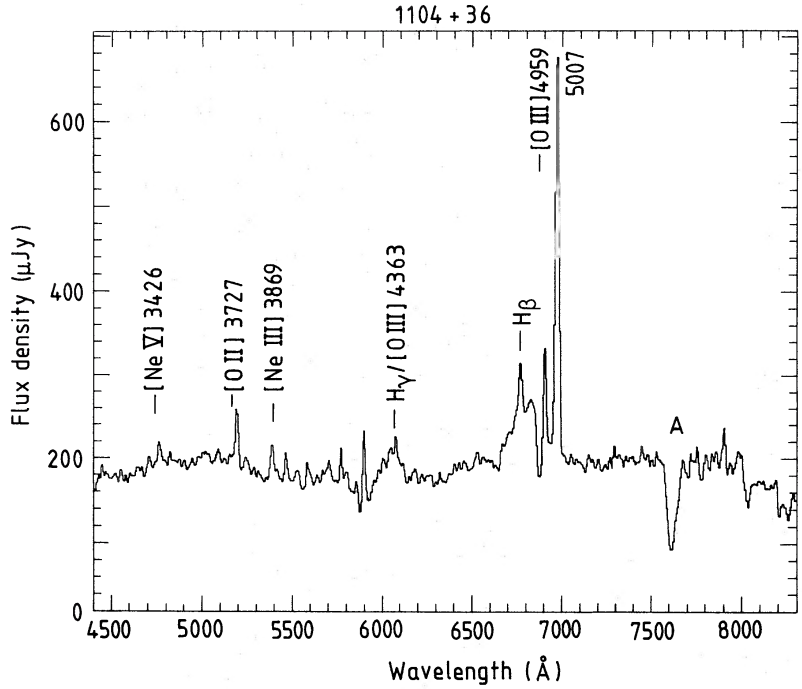


Figure 1 – *continued*

broad emission lines and a power-law continuum. APLGW's classifications were based largely on the measured width of the optical images. Re-examination of their CCD data shows that the object is non-circular but lacks diffuse structure and so, morphologically, is most likely to be an N-galaxy. The radio data do not help us in classifying the object, since the source has double structure with no central component and a steep radio spectrum consistent with it being either a radio galaxy or steep-spectrum quasar. The redshift of 1.39 (with a relatively large uncertainty



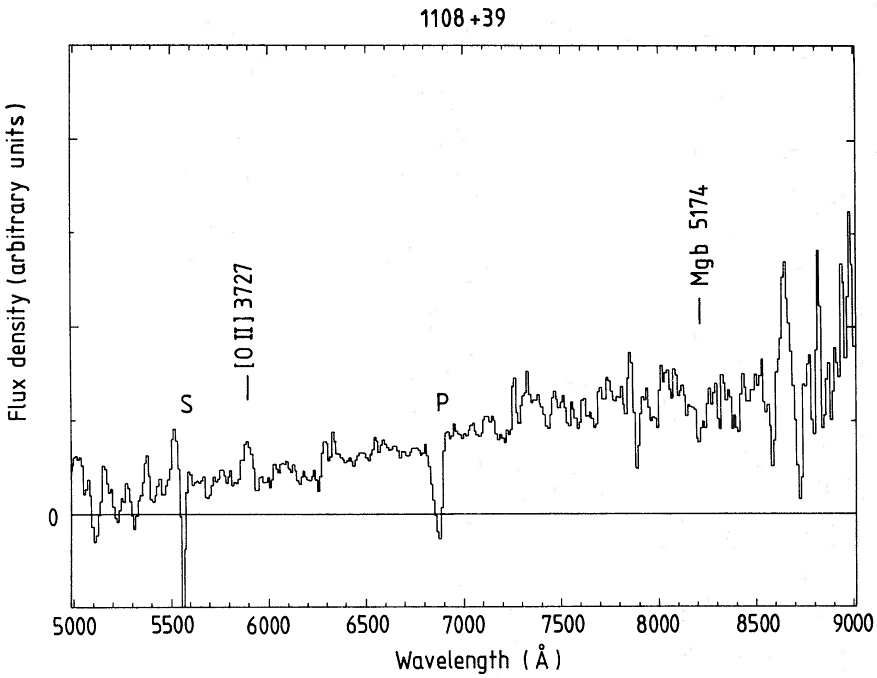
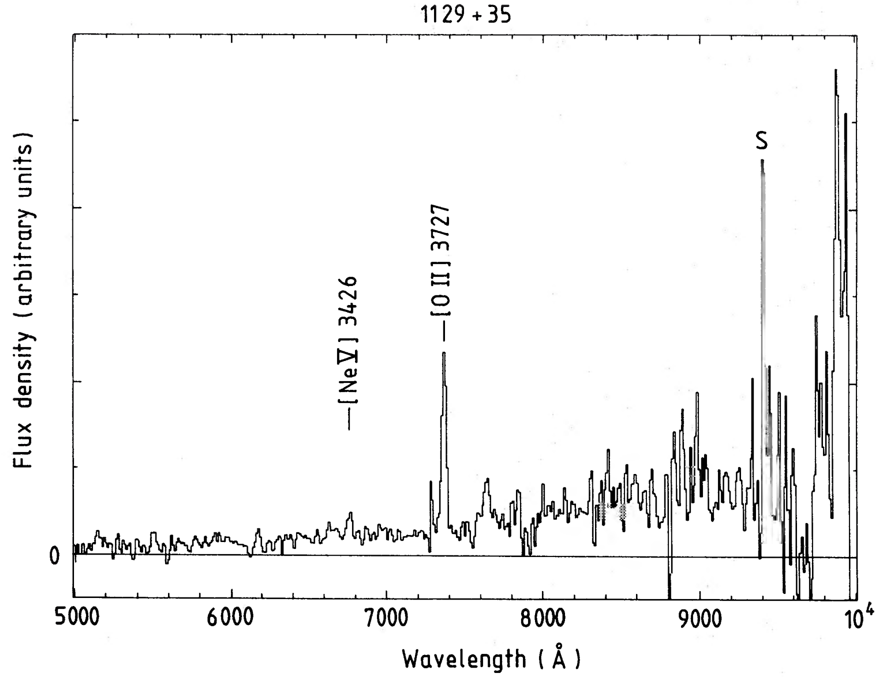


Figure 1 – *continued*

because of the difficulty in measuring the central wavelength of the two broad lines) means the object has an optical luminosity typical of a radio-loud QSO.

1018+37. This spectrum shows two narrow emission lines identified with [O II] λ3727 and [Ne III] λ3869 yielding a redshift of 0.806. The object is probably a narrow emission-line galaxy of the type seen in Paper I and in many 3C galaxies (e.g. Perryman *et al.* 1984; Spinrad & Djorgovsky 1984).

1025+39. This is a low-excitation narrow-line radio galaxy with a redshift of 0.361.



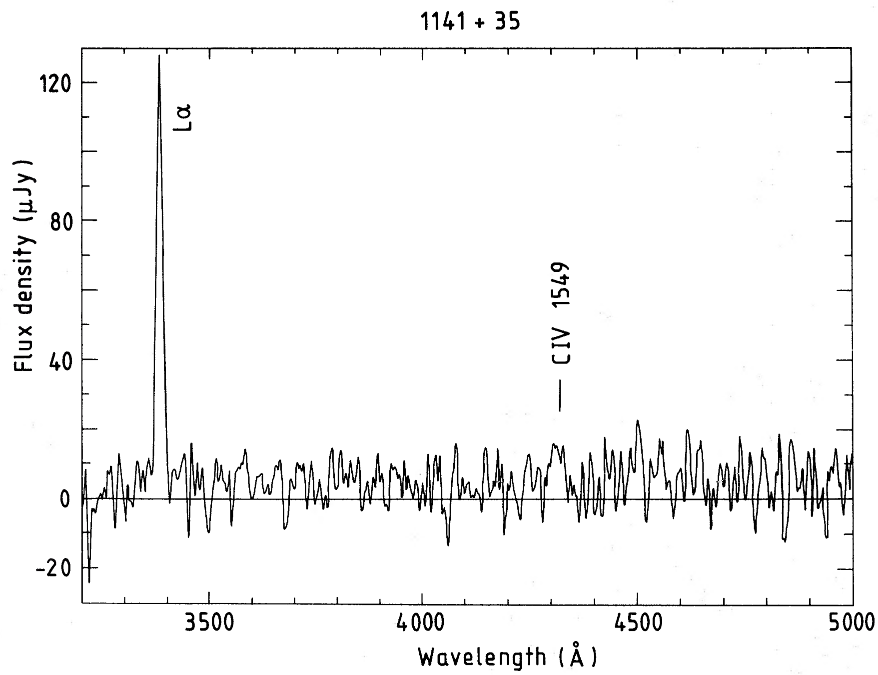


Figure 1 – *continued*

1049+38. This object has a high-excitation narrow emission-line system with weak or absent Balmer emission and broad Mg II λ2799 emission. Weak stellar-absorption features may also be present. The absence of (broad) Hβ may be due to night-sky contamination at long wavelengths. APLGW classified this object as a possible QSO but the CCD image is very faint and there is some trace of diffuse structure. With a redshift of 1.018, the optical luminosity is typical of that of a radio galaxy as is its optical–infrared colour (Lilly *et al.* 1985). Spectroscopically, the narrow

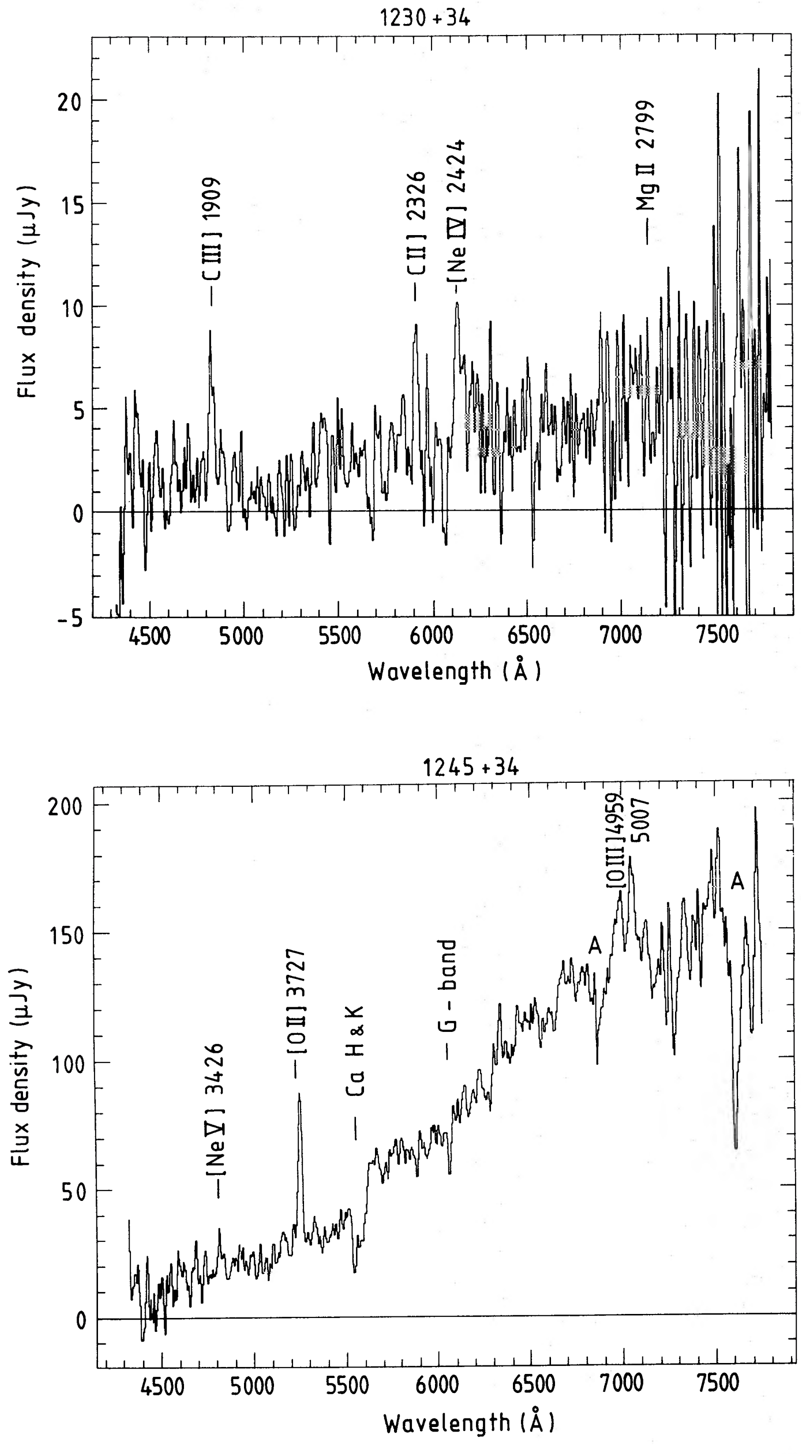


Figure 1 – *continued*

emission lines are galaxy-like but the [O II]/[Ne III] ratio may be more typical of an N-galaxy. The classification of this object is therefore unclear.

1104+36. Another high-excitation spectrum but this time with strong Balmer emission. Hβ is broad and double-peaked perhaps due to the superposition of a narrow line on a possibly asymmetric or displaced broad line (*cf.* 3C 227 – Osterbrock, Koski & Phillips 1976). The 'narrow' peak is at the same redshift as the forbidden lines (0.393). Hγ is present either as a single

Table 2. Line identifications.

Name (B2)	Line ID	Rest wavelength (Å)	Observed wavelength (Å)	Equivalent width (Å)	Flux (10^{-19} Wm^{-2})	redshift
0824+35A	CIV	1549	5034			2.250
	CIII]	1909	6201	26		2.248
0835+37	[OII]	3727	5206	54	7.1	0.396
	[OIII]	5007	6989	9	2.9	0.396
0913+39	MgII?	2799	6351	20		1.269?
0955+38A	CIII]	1909	4564	20	16	1.391
	MgII	2799	6727	69	44	1.403
1018+37	[OII]	3727	6732	83:	8.2	0.806
	[NeIII]	3869	6985	33:	2.6	0.805
1025+39	[OII]	3727	5077	60	44	0.362
	[OIII]	4959	6751			0.361
	[OIII]	5007	6819	14	25	0.362
1049+38	MgII	2799	5651	109		1.019
	[NeV]	3346	6752	10		1.018
	[NeV]	3426	6917	29		1.019
	[OII]	3727	7520	55		1.018
	[NeIII]	3869	7807	49		1.018
	Ca K	3933	7964			1.025
	[NeIII]	3968	8020	16		1.021
	G-band	4304	8650			1.010
	[OIII]	4363	8812	107		1.020
	Hβ	4861	9807			1.017
	[OIII]	4959	10005	200		1.018
	[OIII]	5007	10099	195		1.017
1104+36	[NeV]	3426	4764	4	6.9	0.390
	[OII]	3727	5192	4	1.4	0.393
	[OIII]/Hγ	4350:	6076			0.397:
	[OIII]	4959	6907	14	2.2	0.393
	[OIII]	5007	6973	46	7.4	0.393
1108+39	[OII]	3727	5912	26		0.586
	4000Å break	4000	6310:			0.578:
	Mgb	5174	8240			0.593
1129+35	[NeV]	3426	6751	20:		0.971
	[OII]	3727	7345	119		0.971
	[NeIII]	3869	7628	58		0.972
	[NeIII]	3968	7816			0.970
	[OIII]	5007	9870	204		0.971
1141+35	Lα	1216	3381	100	47	1.781
	CIV	1549	4313	30:	6:	1.783:
	CIII]	1909	5310	10	0.8	1.782
1230+34	CIII]	1909	4828	60	3.0	1.529
	CII]	2326	5915		2.0	1.543
	[NeIV]	2424	6136		2.5	1.531
	MgII	2799	7073		2.0	1.527
1245+34	[OII]	3727	5254	40	17	0.410
	[OIII]	4959	6985		4:	0.409
	[OIII]	5007	7052		5.5	0.408

broad line at the same apparent redshift as the putative peak of the broad Hβ component (0.403) or in a blend with [O III]λ4363. APLGW and Grueff & Vigotti (1979) classified this object as a galaxy and indeed the CCD image of APLGW does show some diffuse structure, although the image may be distorted by its proximity to a defective CCD column. Our spectrum shows no evidence for stellar absorption features. With a redshift of 0.393, this object is intermediate in optical luminosity between that of a normal radio galaxy and a quasar, and its optical–infrared colour is blue.

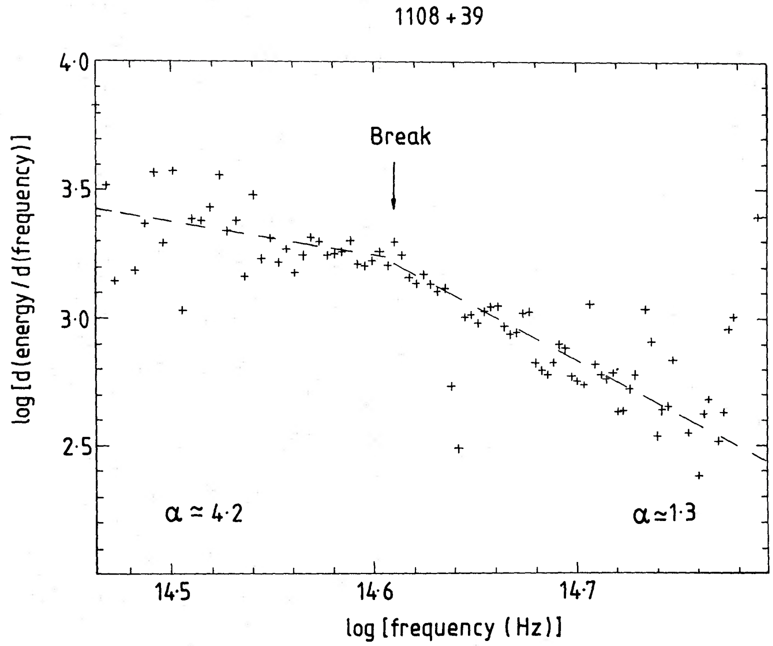


Figure 2. Spectrum of B2 1108+39 resampled in equal intervals of $\log\nu$ to show the break in the spectrum. See the text for further details.

1108+39. This spectrum shows weak [O II]λ3727 emission, Mgb absorption and possibly the 4000 Å break indicating a redshift of about 0.59. This value is supported by a comparison of the spectrum plotted in $\log(dE/d\nu)$ versus $\log\nu$ coordinates (Fig. 2) with that of a typical radio galaxy spectrum with no non-thermal continuum such as 3C31 (Yee & Oke 1978). Both have similar spectral shapes with the same well-defined break at $\log\nu$ (*observed*)$=14.61\pm0.01$ in 1108+39 and $\log\nu$ (*restframe*)$=14.810\pm0.005$ in 3C31. This yields a redshift 0.59 ± 0.01 which is in agreement with the redshift derived from the line identifications. This object was originally classified as a QSO by APLGW but has the spectrum, optical luminosity and colour of a normal radio galaxy.

1129+35. This spectrum shows a low-excitation narrow-line system and a steep ($\alpha\simeq4$) power-law continuum. No Balmer lines are present although Hβ may have been badly affected by night-sky contamination. Neither is broad Mg IIλ2799 present and there are no clear stellar absorption features. APLGW classified this as a QSO although the image is very faint. Without any visible broad-line component, it is hard to confirm this classification although the low excitation is more typical of a galaxy. The steep power-law spectrum could be obtained by simply shifting a normal giant elliptical galaxy spectrum to this redshift (see the note on 1108+39 above) and so does not constitute evidence that this object is a QSO. With a redshift of 0.971, it has the luminosity of a typical radio galaxy (no colour information is available for this object). This object defies straightforward classification but may be one of an intermediate class of object like 1049+39 and 1104+36.

1141+35. The spectrum of this very faint galaxy shows strong narrow Lyα, C IVλ1549 and marginal C III]λ1909 yielding a redshift of 1.781 making it one of the highest-redshift radio galaxies known. The Lα/C IV intensity ratio is $\simeq$8. This is somewhat higher than for 3CR radio galaxies with Lyα emission, e.g. 3C256 and 3C239 (Spinrad *et al.* 1985b) and very much greater than for typical QSOs. The ratio is most like that of a high-excitation Seyfert 2 galaxy. The C IV/C III] ratio is poorly defined but is $\simeq$8 which is very much higher than for the 3CR galaxies or indeed for a Seyfert 2 galaxy. Moreover there is no trace of He IIλ1640 emission which is quite prominent in the spectra of the 3CR galaxies. It is interesting to note that the equivalent width of Lyα is only one third that of 3C256 and 3C239. This may reflect the tendency of 1-Jy galaxies to have weaker emission lines than 3C galaxies at the same redshift as was noted by Allington-Smith *et al.* (1985) and which is discussed further in the next section.

1230+34. The spectrum of this very faint galaxy shows a high-excitation narrow emission-line system. The redshift is 1.533. The spectrum is qualitatively similar to that of 3CR radio galaxies of similar high redshift (Spinrad & Djorgovsky 1984; Spinrad *et al.* 1985b) since, like them, it has strong [Ne IV] emission and a C III]/C II] ratio around unity. This suggests a higher mean ionization level than is typical of radio galaxies at lower redshift (e.g. Allington-Smith *et al.* 1985).

1245+34. This galaxy has a low-excitation narrow emission-line spectrum and a normal elliptical galaxy continuum. The redshift is 0.409.

Three further identifications were observed, 0927+35, 1125+37 and 1225+36, all of which were classified by APLGW as QSOs. The first two have strong power-law continua (α=2.3 and 1.6, respectively) which support the original classifications. 1225+36 showed only a weak continuum but it is perhaps possible to identify two features with Hα and Hβ, in which case the redshift would be 0.42.

4 Discussion

The faint radio source identifications studied in this paper fall into three groups.

(i) Narrow-line radio galaxies of the type familiar from Paper I and from the 3C sample (e.g. Perryman *et al.* 1984; Spinrad & Djorgovsky 1984). These have low-excitation narrow emission-lines, typical giant elliptical continua and have clearly extended optical images.

(ii) Quasars with broad Balmer and permitted lines, non-stellar continua (α=1–2) and compact optical morphology.

(iii) An intermediate class of object which show some of the characteristics of both (a) and (b) and which may, therefore have a significant non-stellar component in their optical spectra. These may be high-redshift analogues of the broad-line radio galaxies or N-galaxies found in the 3C sample. 3C 173 (z=1.035, Djorgovski *et al.,* in preparation) may also belong to this group.

In Paper I, it was reported that a comparison of sub-samples of 3C and 1-Jy galaxies in the redshift range $0.40<z<0.55$ indicated that the equivalent widths of the 1-Jy galaxies were, on average, a factor of 2 weaker than those in the 3C samples. With the addition of two new galaxy redshifts in this interval we may be reasonably sure that our 1-Jy sub-sample is now complete so

Table 3. Comparison of rest-frame [O II]λ3727 equivalent widths.

3CR galaxies				1-Jy galaxies			
name (3C)	z	equivalent width (Å)	rank	name (B2)	z	equivalent width (Å)	rank
330	0.55	155	1	0835+37	0.40	54	1
99	0.43	95	2	0854+39	0.53	52	2
275	0.48	88	3	1245+34	0.41	40	3
244.1	0.43	74	4	1301+38A	0.47	34	4
295	0.46	73	5	0822+34A	0.41	30	5
435	0.47	68	6	1201+39	0.45	21	6
313	0.46	66	7	0847+37	0.41	17	7
457	0.43	59	8	1130+34	0.51	16	8
341	0.45	41	9				
16	0.41	38	10				
411	0.47	30	11				
200	0.46	8	12				
mean		66		mean		33	
median		67		median		32	
s.d.		38		s.d.		16	

we have re-examined the result. The rest-frame [O II] λ3727 equivalent widths of the 3C and 1-Jy galaxies are shown in Table 3 together with a summary of the results of the comparison. The results confirm the conclusion of Paper I. As suggested then, this difference may reflect the fact that the 1-Jy radio galaxies are a factor of ~5 less radio luminous than those in the 3C sample and therefore suggests an underlying relationship between the large-scale radio emission and the small-scale activity in the narrow-line region.

Further analysis of these results will be presented in the next paper.

5 Conclusions

We have obtained redshifts for 13 (1 provisional) faint identifications of radio sources in the 1-Jy radio-selected sample. Most of the galaxy identifications have narrow emission-line systems and normal elliptical galaxy continua but two show evidence for a non-stellar radiation component. Likewise, two of the five quasar candidates may be similarly classified as having properties intermediate between those of normal (narrow line) radio galaxies and quasars. We confirm that the 1-Jy galaxies have emission lines that are a factor of 2 weaker than those of the more radio luminous 3C galaxies at the same redshift. Two of the galaxies have redshifts $z > 1.5$.

Acknowledgments

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Note added in proof

More recent observations have confirmed the redshift of 0913+39.

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